

# Forward dijets in $pA$ and $\gamma A$ collisions within the small- $x$ improved TMD factorization framework

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in collaboration with:

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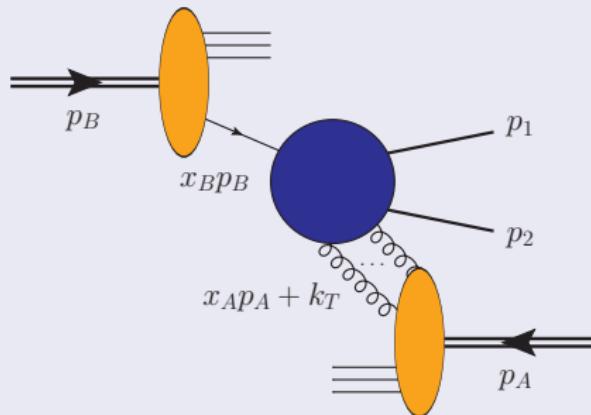
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DE-FG02-93ER40771

# Outlook

- Phenomenology for forward dijet production in  $pA$  and  $\gamma A$  (realized by ultra-peripheral heavy ion collisions) for LHC kinematics
- **Framework:** a formalism interpolating between the leading twist limit of the Color Glass Condensate (which includes saturation) and the High Energy (or  $k_T$ ) factorization which includes all twists (linear regime)

# Dijets in dilute-dense $pA$ collisions

## Hybrid approach<sup>1</sup>



forward dijets with transverse momentum imbalance:

$$|\vec{p}_{T1} + \vec{p}_{T2}| = |\vec{k}_T| = k_T$$

asymmetric kinematics:

$$x_B \gg x_A$$

- large- $x$  parton in hadron  $B$  is treated as 'collinear' with standard PDFs
- small- $x$  partons within hadron  $A$  have internal transverse momentum  $k_T$

## Three-scale problem

- ① hard scale  $P_T$  (of the order of the average transverse momentum of jets)
- ② transverse momentum imbalance  $k_T$
- ③ saturation scale  $\Lambda_{\text{QCD}} \ll Q_s$  (increasing with energy)

<sup>1</sup> A. Dumitru, J. Jalilian-Marian, Phys. Lett. B 547 (2001)

# Color Glass Condensate (CGC): $Q_s \sim k_T \sim P_T$

Example:  $qA \rightarrow qg$  channel<sup>1</sup>

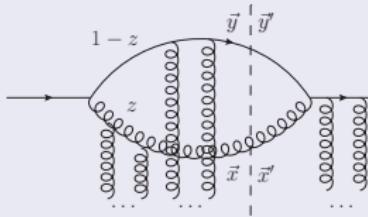
$$\frac{d\sigma_{qA \rightarrow 2j}}{d^3 p_1 d^3 p_2} \sim \int \frac{d^2 x}{(2\pi)^2} \frac{d^2 x'}{(2\pi)^2} \frac{d^2 y}{(2\pi)^2} \frac{d^2 y'}{(2\pi)^2} e^{-i\vec{p}_{T1} \cdot (\vec{x}_T - \vec{x}'_T)} e^{-i\vec{p}_{T2} \cdot (\vec{y}_T - \vec{y}'_T)} \psi_z^* (\vec{x}'_T - \vec{y}'_T) \psi_z (\vec{x}_T - \vec{y}_T)$$

$$\left\{ S_{x_g}^{(6)} (\vec{y}_T, \vec{x}_T, \vec{y}'_T, \vec{x}'_T) - S_{x_g}^{(3)} (\vec{y}_T, \vec{x}_T, (1-z)\vec{y}'_T + z\vec{x}'_T) - S_{x_g}^{(3)} ((1-z)\vec{y}_T + z\vec{x}_T, \vec{y}'_T, \vec{x}'_T) \right.$$

$$\left. - S_{x_g}^{(2)} ((1-z)\vec{y}_T + z\vec{x}_T, (1-z)\vec{y}'_T + z\vec{x}'_T) \right\}$$

$\psi_z (\vec{x}_T)$  – quark wave function

$S_{x_g}^{(i)}$  – correlators of Wilson line operators, e.g.



$$S_{x_g}^{(2)} (\vec{y}_T, \vec{x}_T) = \frac{1}{N_c} \langle \text{Tr} [U(\vec{y}_T) U^\dagger(\vec{y}'_T)] \rangle_{x_g}$$

$$S_{x_g}^{(3)} (\vec{z}_T, \vec{y}_T, \vec{x}_T) = \frac{1}{2C_F N_c} \langle \text{Tr} [U(\vec{z}_T) U^\dagger(\vec{y}_T)] \text{Tr} [U(\vec{y}_T) U^\dagger(\vec{x}_T)] \rangle_{x_g} - S_{x_g}^{(2)} (\vec{z}_T, \vec{x}_T) \text{ etc.}$$

where  $U(\vec{x}_T) = U(-\infty, +\infty; \vec{x}_T)$ ,  $U(a, b; x_T) = \mathcal{P} \exp \left[ ig \int_a^b dx^+ A_a^-(x^+, x_T) t^a \right]$ .

$\langle \dots \rangle_{x_g}$  denotes the average over background color field.

<sup>1</sup> C. Marquet, Nucl. Phys. A 796 (2007) 41

# High energy factorization (HEF): $k_T \sim P_T \gg Q_s$

$k_T$  factorization formula<sup>1,2,3,4</sup>

$$d\sigma_{AB \rightarrow 2j} = \sum_b \int dx_A dx_B \int dk_T^2 \mathcal{F}(x_A, k_T^2, \mu^2) f_{b/B}(x_B, \mu^2) d\hat{\sigma}_{g^* b \rightarrow 2j}(x_A, x_B, k_T^2, \mu^2)$$

$\mathcal{F}(x_A, k_T^2, \mu^2)$  – Unintegrated Gluon Distribution (UGD) evolving via BFKL, or better via extensions involving DGLAP corrections like Kimber-Martin-Ryskin (KMR), Kwiecinski-Martin-Stasto (KMS) or CCFM.

$f_{b/B}(x_B, \mu^2)$  – collinear PDF

$\hat{\sigma}_{g^* b \rightarrow 2j}$  – partonic cross section, computed with off-shell incoming gluon in a gauge invariant way. Methods for gauge invariant off-shell amplitudes:

[E. Antonov, L. Lipatov, E. Kuraev, I. Cherednikov, Nucl.Phys. B721 (2005) 111-135]

[A. van Hameren, PK, K. Kutak, JHEP 1212 (2012) 029; JHEP 1301 (2013) 078]

[PK, JHEP 1407 (2014) 128]

[A. van Hameren, JHEP 1407 (2014) 138]

[A. van Hameren, M. Serino, JHEP 1507 (2015) 010]

No saturation in this formalism (although one can 'inject' it by using nonlinear UGD).

<sup>1</sup> L.V. Gribov, E.M. Levin, M.G. Ryskin, Phys.Rept. 100 (1983) 1-150

<sup>2</sup> J.C. Collins, R.K. Ellis, Nucl.Phys. B360 (1991) 3-30

<sup>3</sup> S. Catani, M. Ciafaloni, F. Hautmann, Nucl.Phys. B366 (1991) 135-188

<sup>4</sup> M. Deak, F. Hautmann, H. Jung, K. Kutak, JHEP 0909 (2009) 121 (hybrid)

# Generalized TMD factorization: $P_T \gg k_T \sim Q_s$

Leading twist formula with several process-dependent TMD gluons<sup>1,2</sup>

$$\frac{d\sigma_{AB \rightarrow 2j}}{dy_1 d^2 p_{T1} dy_2 d^2 p_{T1}} \sim \sum_{a,c,d} f_{a/B}(x_B, P_T^2) \sum_i \mathcal{F}_{ag}^{(i)}(x_A, k_T^2) H_{ag \rightarrow cd}^{(i)}(x_A, x_B)$$

$H^{(i)}$  – hard on-shell factors

$\mathcal{F}_{ag}^{(i)}$  – TMD Gluon Distributions with the operator definitions of the type

$$\int \frac{d\xi^+ d^2 \xi}{(2\pi)^3 p_A^-} e^{ix_A p_A^- \xi^+ - i \vec{k}_T \vec{\xi}_T} \langle p_A | \text{Tr} \left\{ F^{-i}(\xi) [\xi, 0]_{C_1} F^{-i}(0) [0, \xi]_{C_2} \right\} | p_A \rangle$$

where the Wilson lines  $[\xi, 0]_{C_i}$  depend on the particular diagram it accompanies. The operator position  $\xi$  is off the light-cone.

<sup>1</sup> F. Dominguez, C. Marquet, B-W. Xiao, F. Yuan Phys.Rev. D 83 (2011) 105005

<sup>2</sup> C.J. Bomhof, P.J. Mulders, F. Pijlman, Eur.Phys.J.C. 47, 147 (2006)

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$$\mathcal{F}_{qg}^{(1)} \sim \langle p_A | \text{Tr} \left\{ F^{-i}(\xi) \mathcal{U}^{[-]\dagger} F^{-i}(0) \mathcal{U}^{[+]}\right\} | p_A \rangle, \quad \mathcal{F}_{qg}^{(2)} \sim \langle p_A | \text{Tr} \left\{ F^{-i}(\xi) \frac{\text{Tr} \mathcal{U}^{[\square]}}{N_c} \mathcal{U}^{[+]\dagger} F^{-i}(0) \mathcal{U}^{[+]}\right\} | p_A \rangle,$$

$$\mathcal{F}_{gg}^{(1)} \sim \langle p_A | \text{Tr} \left\{ F^{-i}(\xi) \frac{\text{Tr} \mathcal{U}^{[\square]}}{N_c} \mathcal{U}^{[-]\dagger} F^{-i}(0) \mathcal{U}^{[+]}\right\} | p_A \rangle, \quad \mathcal{F}_{gg}^{(2)} \sim \frac{1}{N_c} \langle p_A | \text{Tr} \left\{ F^{-i}(\xi) \mathcal{U}^{[\square]\dagger} \right\} \text{Tr} \left\{ F^{-i}(0) \mathcal{U}^{[\square]}\right\} | p_A \rangle,$$

$$\mathcal{F}_{gg}^{(3)} \sim \langle p_A | \text{Tr} \left\{ F^{-i}(\xi) \mathcal{U}^{[+]\dagger} F^{-i}(0) \mathcal{U}^{[+]}\right\} | p_A \rangle, \quad \mathcal{F}_{gg}^{(4)} \sim \langle p_A | \text{Tr} \left\{ F^{-i}(\xi) \mathcal{U}^{[-]\dagger} F^{-i}(0) \mathcal{U}^{[-]}\right\} | p_A \rangle,$$

$$\mathcal{F}_{gg}^{(5)} \sim \langle p_A | \text{Tr} \left\{ F^{-i}(\xi) \mathcal{U}^{[\square]\dagger} \mathcal{U}^{[+]\dagger} F^{-i}(0) \mathcal{U}^{[\square]} \mathcal{U}^{[+]}\right\} | p_A \rangle, \quad \mathcal{F}_{gg}^{(6)} \sim \langle p_A | \text{Tr} \left\{ F^{-i}(\xi) \mathcal{U}^{[+]\dagger} F^{-i}(0) \mathcal{U}^{[+]}\right\} \left( \frac{\text{Tr} \mathcal{U}^{[\square]}}{N_c} \right)^2 | p_A \rangle$$

$$\mathcal{U}^{[\pm]} = U(0, \pm\infty; 0_T) U(\pm\infty, \xi^+; \xi_T) \quad \mathcal{U}^{[\square]} = \mathcal{U}^{[+]} \mathcal{U}^{[-]\dagger} = \mathcal{U}^{[-]} \mathcal{U}^{[+]\dagger}$$

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# Generalized TMD factorization

Is it usable?

It can be compared with the CGC results in the back-to-back limit ( $k_T \ll P_T$ ).

In the large  $N_c$  and the gaussian approximation this leads to an effective factorization

⇒ all UGDs can be expressed<sup>1</sup> by only two fundamental<sup>2</sup> UGDs (but related in this limit):

$$\mathcal{F}_{qg}^{(2)}(x, k_T^2) \sim \int \frac{d^2 q_T}{q_T^2} \mathcal{F}_{gg}^{(3)}(x, q_T^2) \mathcal{F}_{qg}^{(1)}(x, |k_T - q_T|^2)$$

$$\mathcal{F}_{gg}^{(1)}(x, k_T^2) \sim \int \frac{d^2 q_T}{q_T^2} \mathcal{F}_{qg}^{(1)}(x, q_T^2) \mathcal{F}_{qg}^{(1)}(x, |k_T - q_T|^2)$$

$$\mathcal{F}_{gg}^{(2)}(x, k_T^2) \sim \int \frac{d^2 q_T}{q_T^2} (q_T - k_T) \cdot q_T \mathcal{F}_{qg}^{(1)}(x, q_T^2) \mathcal{F}_{qg}^{(1)}(x, |k_T - q_T|^2)$$

$$\mathcal{F}_{gg}^{(1)}(x, k_T^2) \sim \int \frac{d^2 q_T d^2 q'_T}{q_T^2} \mathcal{F}_{gg}^{(3)}(x, q_T^2) \mathcal{F}_{qg}^{(1)}(x, q'_T^2) \mathcal{F}_{qg}^{(1)}(x, |k_T - q_T - q'_T|^2)$$

- ① dipole:  $\mathcal{F}_{qg}^{(1)} = xG^{(2)} \sim \langle p_A | \text{Tr}\{F(\xi) \mathcal{U}^{[-]\dagger} F(0) \mathcal{U}^{[+]}\} | p_A \rangle$

appears directly in: inclusive DIS, inclusive jet in  $pA$

- ② Weizsäcker-Williams (WW):  $\mathcal{F}_{gg}^{(3)} = xG^{(1)} \sim \langle p_A | \text{Tr}\{F(\xi) \mathcal{U}^{[+]\dagger} F(0) \mathcal{U}^{[+]}\} | p_A \rangle$

appears directly in dijets in DIS

<sup>1</sup> F. Dominguez, C. Marquet, B-W. Xiao, F. Yuan Phys.Rev. D 83 (2011) 105005

<sup>2</sup> Dmitri Kharzeev, Yuri V. Kovchegov, Kirill Tuchin, Phys.Rev. D68 (2003) 094013

# Improved TMD factorization (ITMD): $P_T \gg Q_s$

Improved factorization formula having two limiting cases<sup>1</sup>

- ① Generalized TMD when  $P_T \gg k_T$  (saturation)
- ② High Energy Factorization when  $P_T \sim k_T$  (jet decorrelation regime)

$$\frac{d\sigma_{AB}}{dy_1 d^2 p_{T1} dy_2 d^2 p_{T1}} \sim \sum_{a,c,d} f_{a/B}(x_B, P_T^2) \sum_{i=1,2} \Phi_{ag \rightarrow cd}^{(i)}(x_A, k_T^2) K_{ag \rightarrow cd}^{(i)}(x_A, x_B, k_T)$$

<sup>1</sup> P.K., K. Kutak, C. Marquet, E. Petreska, S. Sapeta, A. van Hameren, JHEP 1509 (2015) 106

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$$\Phi_{qg \rightarrow gq}^{(1)} = \mathcal{F}_{qg}^{(1)}, \quad \Phi_{qg \rightarrow gq}^{(2)} = \frac{1}{N_c^2 - 1} \left( N_c^2 \mathcal{F}_{qg}^{(2)} - \mathcal{F}_{qg}^{(1)} \right), \quad \Phi_{gg \rightarrow q\bar{q}}^{(1)} = \frac{1}{N_c^2 - 1} \left( N_c^2 \mathcal{F}_{gg}^{(1)} - \mathcal{F}_{gg}^{(3)} \right), \quad \Phi_{gg \rightarrow q\bar{q}}^{(2)} = \mathcal{F}_{gg}^{(3)} - N_c^2 \mathcal{F}_{gg}^{(2)}$$

$$\Phi_{gg \rightarrow gg}^{(1)} = \frac{1}{2N_c^2} \left( N_c^2 \mathcal{F}_{gg}^{(1)} - 2\mathcal{F}_{gg}^{(3)} + \mathcal{F}_{gg}^{(4)} + \mathcal{F}_{gg}^{(5)} + N_c^2 \mathcal{F}_{gg}^{(6)} \right), \quad \Phi_{gg \rightarrow gg}^{(2)} = \frac{1}{N_c^2} \left( N_c^2 \mathcal{F}_{gg}^{(2)} - 2\mathcal{F}_{gg}^{(3)} + \mathcal{F}_{gg}^{(4)} + \mathcal{F}_{gg}^{(5)} + N_c^2 \mathcal{F}_{gg}^{(6)} \right)$$

$$K_{qg \rightarrow gq}^{(1)} = -\frac{\bar{u}(\bar{s}^2 + \bar{u}^2)}{2\hat{t}\hat{u}\hat{s}} \left( 1 + \frac{\bar{s}\hat{s} - \hat{t}\hat{t}}{N_c^2 \bar{u}\hat{u}} \right), \quad K_{qg \rightarrow gq}^{(2)} = -\frac{C_F}{N_c} \frac{\bar{s}(\bar{s}^2 + \bar{u}^2)}{\hat{t}\hat{u}\hat{u}}, \quad K_{gg \rightarrow q\bar{q}}^{(1)} = \frac{1}{2N_c} \frac{(\hat{t}^2 + \bar{u}^2)(\bar{u}\hat{u} + \hat{t}\hat{t})}{\bar{s}\hat{s}\hat{t}\hat{u}}$$

$$K_{gg \rightarrow q\bar{q}}^{(2)} = \frac{1}{4N_c^2 C_F} \frac{(\hat{t}^2 + \bar{u}^2)(\bar{u}\hat{u} + \hat{t}\hat{t} - \bar{s}\hat{s})}{\bar{s}\hat{s}\hat{t}\hat{u}}, \quad K_{gg \rightarrow q\bar{q}}^{(2)} = \frac{1}{4N_c^2 C_F} \frac{(\hat{t}^2 + \bar{u}^2)(\bar{u}\hat{u} + \hat{t}\hat{t} - \bar{s}\hat{s})}{\bar{s}\hat{s}\hat{t}\hat{u}},$$

$$K_{gg \rightarrow gg}^{(1)} = \frac{N_c}{C_F} \frac{(\bar{s}^4 + \hat{t}^4 + \bar{u}^4)(\bar{u}\hat{u} + \hat{t}\hat{t})}{\hat{t}\hat{u}\hat{u}\bar{s}\hat{s}}, \quad K_{gg \rightarrow gg}^{(2)} = -\frac{N_c}{2C_F} \frac{(\bar{s}^4 + \hat{t}^4 + \bar{u}^4)(\bar{u}\hat{u} + \hat{t}\hat{t} - \bar{s}\hat{s})}{\hat{t}\hat{u}\hat{u}\bar{s}\hat{s}}$$

$\hat{s}, \hat{t}, \hat{u}$  – ordinary Mandelstam variables,  $\hat{s} + \hat{t} + \hat{u} = k_T^2$

$\bar{s}, \bar{t}, \bar{u}$  off-shell momentum is replaced by its longitudinal component of off-shell momentum,  $\bar{s} + \bar{u} + \bar{t} = 0$

<sup>1</sup> P.K., K. Kutak, C. Marquet, E. Petreska, S. Sapeta, A. van Hameren, JHEP 1509 (2015) 106

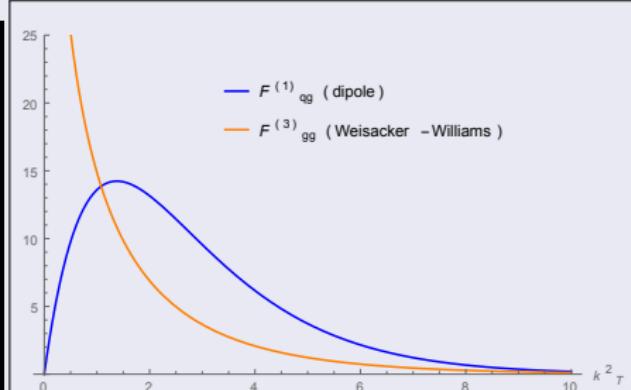
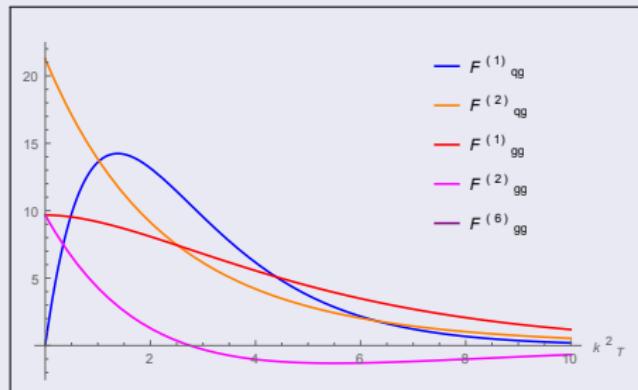
# Gluon distributions: GBW model

How to obtain all gluon distributions?

To start, we take the Golec-Biernat-Wusthoff (GBW) model:

$$xG_2(x, k_T^2) = \mathcal{F}_{qg}^{(1)}(x, k_T^2) = \frac{N_c S_\perp}{2\pi^3 \alpha_s} \frac{k_T^2}{Q_s^2(x)} \exp\left(-\frac{k_T^2}{Q_s^2(x)}\right), \quad Q_s(x) = Q_{s0}^2 \left(\frac{x}{x_0}\right)^{\lambda}$$

Assuming gaussian distribution of colour sources, the WW gluon  $xG_1(x, k_T^2)$  can be related to  $xG_2(x, k_T^2)$ , hence all five gluons can be calculated analytically<sup>1</sup>



<sup>1</sup> E. Petreska, Proceedings, 7th International Workshop MPI@LHC 2015

# Gluon distributions: realistic model

Problem: GBW model has wrong large- $k_T$  behaviour...

More realistic  $\mathcal{F}_{qg}^{(1)}$  is given e.g. by the nonlinear extension<sup>1</sup> of the Kwiecinski-Martin-Stasto<sup>2</sup> (KMS) evolution equation (below  $\mathcal{F}_{qg}^{(1)} \equiv \mathcal{F}$ ):

$$\begin{aligned}\mathcal{F}(x, k_T^2) = & \mathcal{F}_0(x, k_T^2) + \frac{\alpha_s N_c}{\pi} \int_x^1 \frac{dz}{z} \int_{k_T^2 T_0}^{\infty} \frac{dq_T^2}{q_T^2} \left\{ \frac{q_T^2 \mathcal{F}\left(\frac{x}{z}, q_T^2\right) \theta\left(\frac{k_T^2}{z} - q_T^2\right) - k_T^2 \mathcal{F}\left(\frac{x}{z}, k_T^2\right)}{|q_T^2 - k_T^2|} + \frac{k_T^2 \mathcal{F}\left(\frac{x}{z}, k_T^2\right)}{\sqrt{4q_T^4 + k_T^4}} \right\} \\ & + \frac{\alpha_s}{2\pi k_T^2} \int_x^1 dz \left\{ \left( P_{gg}(z) - \frac{2N_c}{z} \right) \int_{k_T^2 T_0}^{k_T^2} dq_T^2 \mathcal{F}\left(\frac{x}{z}, q_T^2\right) + z P_{gq}(z) \Sigma\left(\frac{x}{z}, k_T^2\right) \right\} \\ & - \frac{2\alpha_s^2}{R^2} \left\{ \left[ \int_{k_T^2}^{\infty} \frac{dq_T^2}{q_T^2} \mathcal{F}(x, q_T^2) \right]^2 + \mathcal{F}(x, k_T^2) \int_{k_T^2}^{\infty} \frac{dq_T^2}{q_T^2} \ln\left(\frac{q_T^2}{k_T^2}\right) \mathcal{F}(x, q_T^2) \right\}\end{aligned}$$

This equation was fitted to HERA data for proton by Kutak-Sapeta (KS)<sup>3</sup>.

For nucleus  $R_A = RA^{1/3}$  is used so the nonlinear term is enhanced by  $A^{1/3}$  (in the UGDs per nucleon).

In addition, we vary  $R_A$  by a parameter  $1/d$  to access the theory uncertainty.

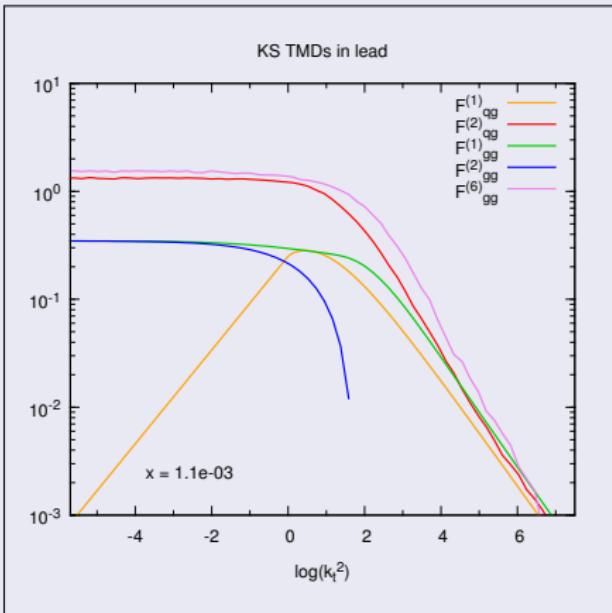
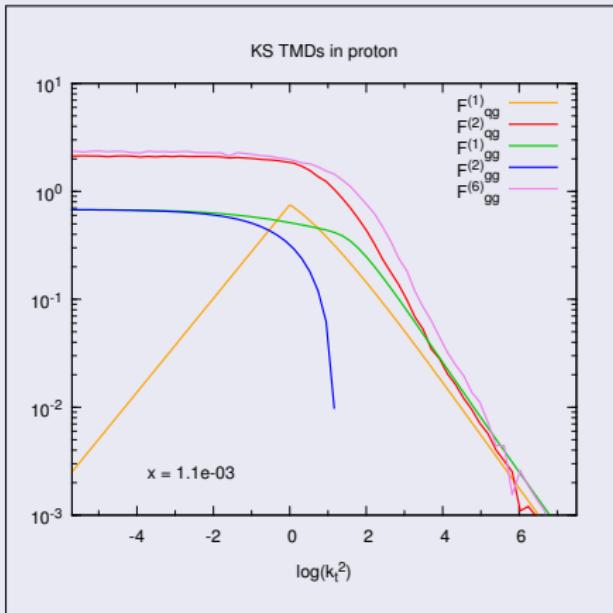
<sup>1</sup> K. Kutak, K. Kwiecinski, Eur. Phys. J. C 29 (2003) 521

<sup>2</sup> J. Kwiecinski, Alan D. Martin, A.M. Stasto, Phys. Rev. D56 (1997) 3991-4006

<sup>3</sup> K. Kutak, S. Sapeta, Phys. Rev. D 86 (2012) 094043

# Gluon distributions: realistic model

Five gluon distributions from KS fit<sup>1</sup>

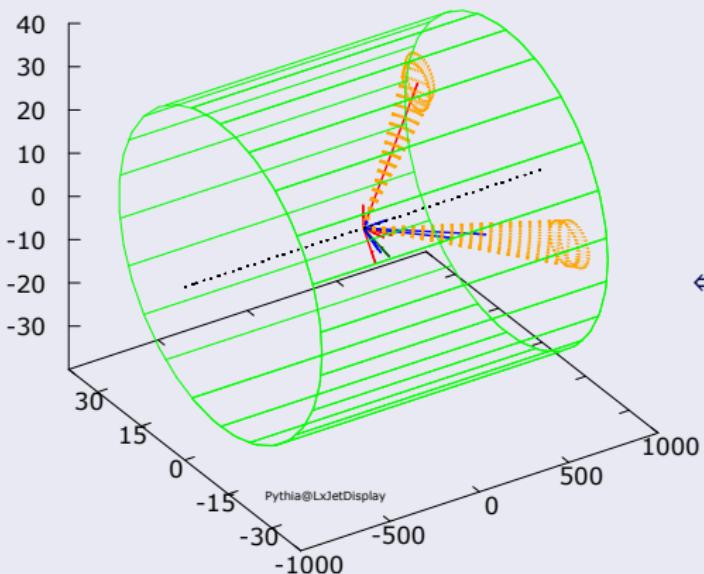


All gluons start to merge for large  $k_T$  (except  $\mathcal{F}_{gg}^{(2)}$  which vanishes)  $\Rightarrow$  correct HEF limit.

<sup>1</sup> A. van Hameren, P.K., K. Kutak, C. Marquet, E. Petreska, S. Sapeta, arXiv:1607.03121

# Dijets in dilute-dense $pA$ collisions

## Realistic setup at LHC



- reconstructed dijet system has the minimal  $p_T$  around  $\sim 20$  GeV
- both jets are forward (in the proton direction) – rapidity  $y$  of  $\sim 3.5$  or more

↙ This event (from PYTHIA):

- jets with  $p_{T1} \sim 27$  GeV,  $p_{T2} \sim 30$  GeV
- $y > 3.5$
- 9 MPI events (not all visible; each in different color)
- jet disbalance  $q_T \sim 10$  GeV

# Results<sup>1</sup> for nuclear modification ratio $R_{p\text{Pb}}$ at LHC

## Kinematic cuts

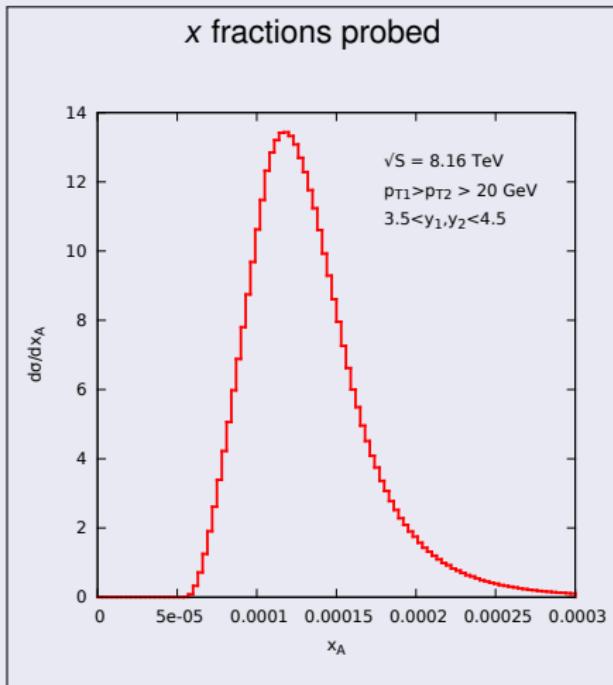
- CM energy:  $\sqrt{S} = 8.16 \text{ TeV}$
- require two jets with  
 $(\Delta\phi)^2 + (\Delta\eta)^2 > R^2, R = 0.5$
- transverse momenta cuts:  
 $p_{T1} > p_{T2} > 20 \text{ GeV}$
- rapidity cuts:  $3.5 < y_1, y_2 < 4.5$

<sup>1</sup> A. van Hameren, P.K., K. Kutak, C. Marquet, E. Petreska, S. Sapeta, arXiv:1607.03121

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## Kinematic cuts

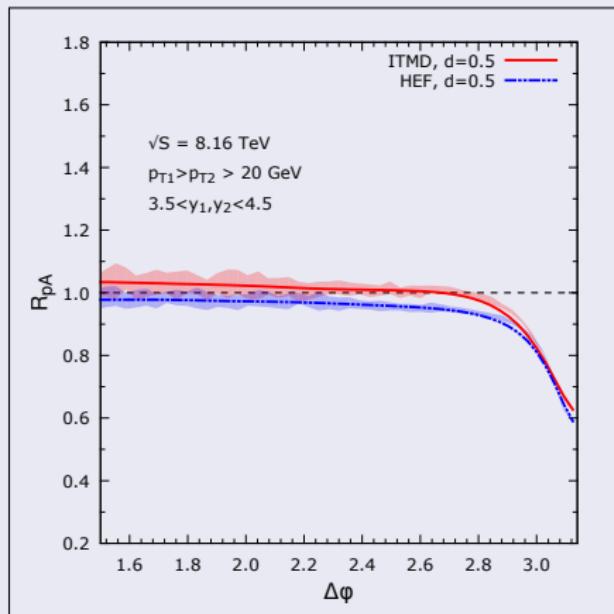
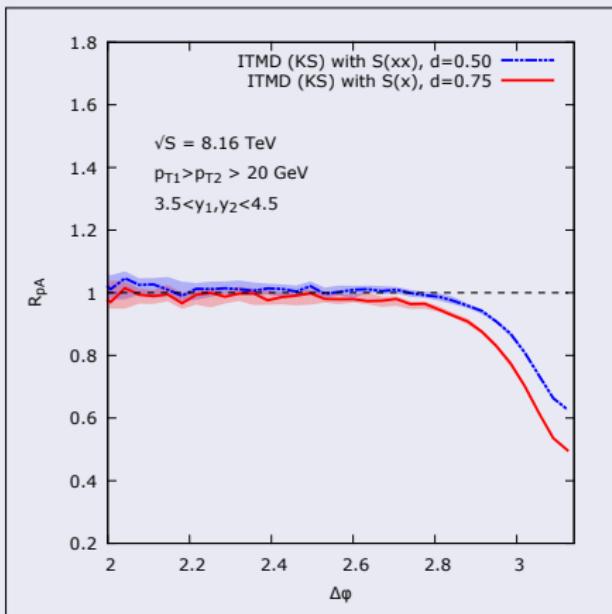
- CM energy:  $\sqrt{S} = 8.16 \text{ TeV}$
- require two jets with  $(\Delta\phi)^2 + (\Delta\eta)^2 > R^2, R = 0.5$
- transverse momenta cuts:  $p_{T1} > p_{T2} > 20 \text{ GeV}$
- rapidity cuts:  $3.5 < y_1, y_2 < 4.5$



<sup>1</sup> A. van Hameren, P.K., K. Kutak, C. Marquet, E. Petreska, S. Sapeta, arXiv:1607.03121

# Results for nuclear modification ratio $R_{p\text{Pb}}$ at LHC

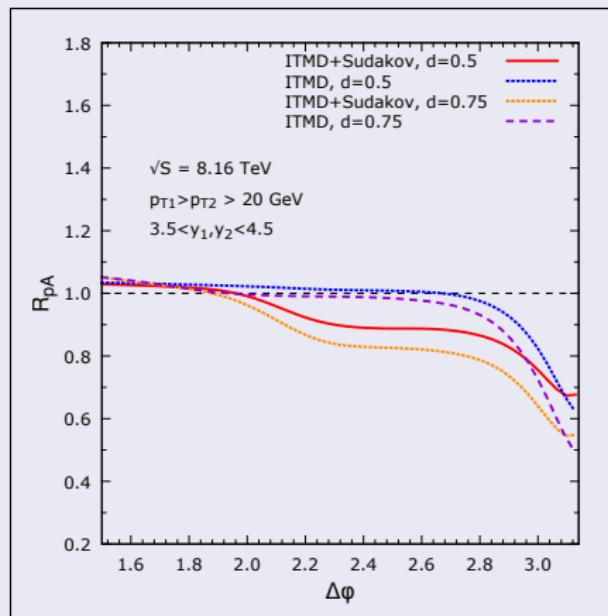
## Azimuthal decorrelations



# Results for nuclear modification ratio $R_{p\text{Pb}}$ at LHC

## Azimuthal decorrelations

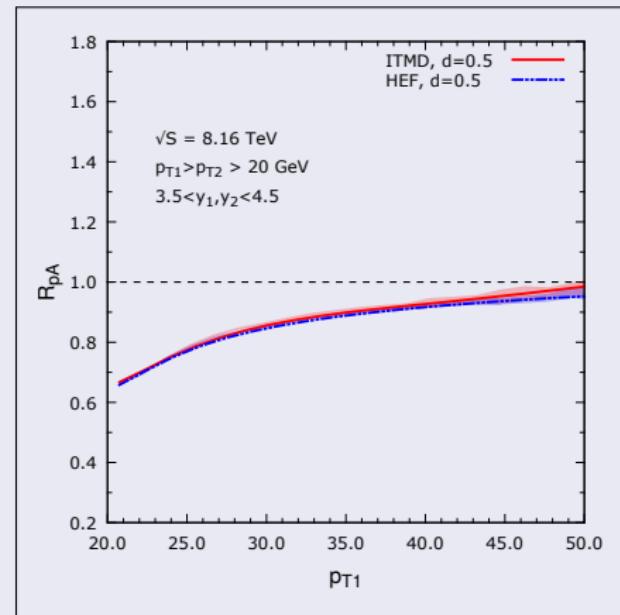
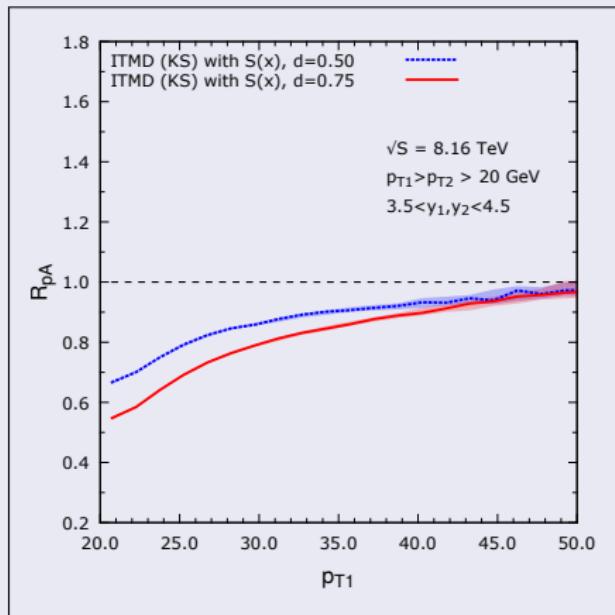
Including Sudakov resummation (a model of):



# Results for nuclear modification ratio $R_{p\text{Pb}}$ at LHC

## Jet $p_T$ spectra

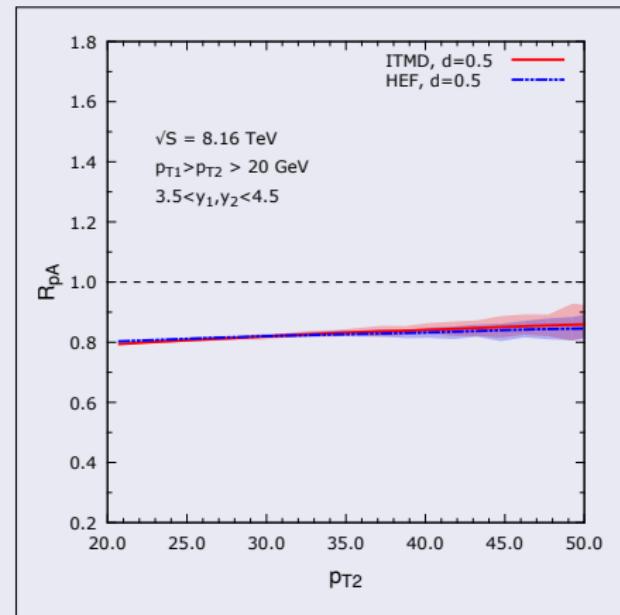
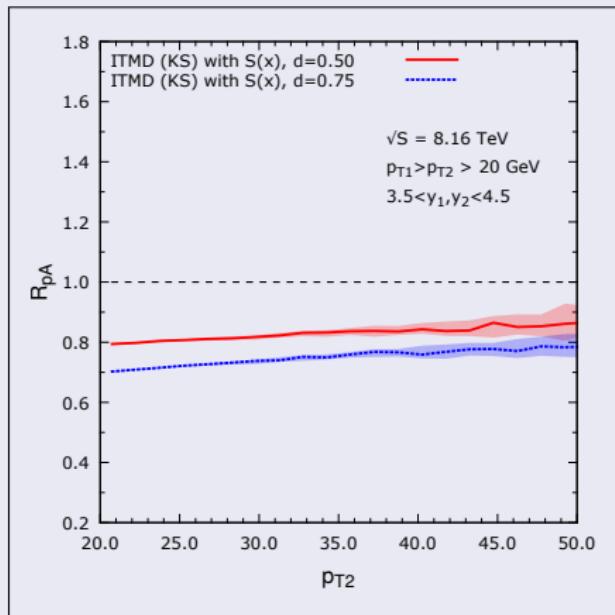
leading jet spectrum:



# Results for nuclear modification ratio $R_{p\text{Pb}}$ at LHC

## Jet $p_T$ spectra

sub-leading jet spectrum:



# The WW gluon distribution issue

## Gaussian approximation

In general WW gluon  $G^{(1)}$  and dipole gluon  $G^{(2)}$  are independent.

They are related only in 'gaussian approximation':

$$\nabla_{k_T}^2 G^{(1)}(x, k_T) = \frac{4\pi^2}{N_c S_\perp} \int \frac{d^2 q_T}{q_T^2} \frac{\alpha_s}{(k_T - q_T)^2} G^{(2)}(x, q_T) G^{(2)}(x, |k_T - q_T|)$$

and this is what was used in our calculations.

- the most basic process WW gluon appears directly is the dijet production in  $\gamma A$  collisions
- there are no fits of this gluon

Can we learn about WW gluon from Ultra Peripheral Collisions at LHC?

# ITMD for Ultra Peripheral Collisions

Factorization formula (direct photon)

$$d\sigma_{AB \rightarrow 2j} \sim \int d\omega \frac{dN_\gamma}{d\omega} G^{(1)}(x_A, k_T^2) K_{\gamma g \rightarrow q\bar{q}}(x_A, x_B, k_T)$$

$\frac{dN_\gamma}{d\omega}$  – photon flux from nucleus,  $\omega = x_B E_{\text{Pb}}$

$K_{\gamma g \rightarrow q\bar{q}}$  – off-shell hard factor for  $\gamma g^* \rightarrow q\bar{q}$  process

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What  $x$  can we probe?

The formalism requires:  
asymmetric kinematics with  
 $x_B > x_A$  and  $x_A$  small

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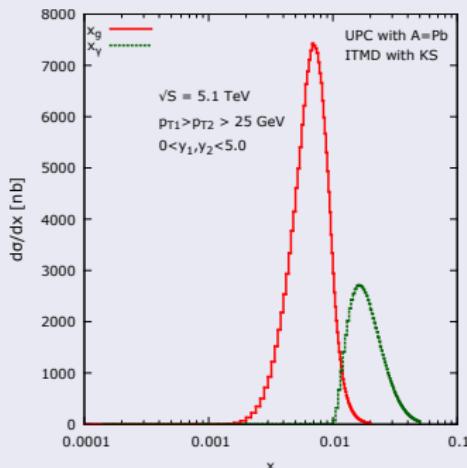
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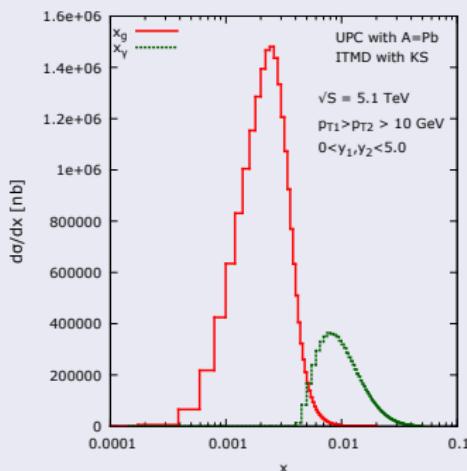
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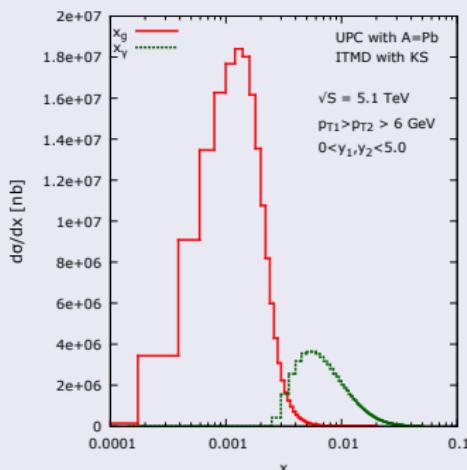
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# ITMD for Ultra Peripheral Collisions

Results for nuclear modification ratios  $R_{\gamma A}$

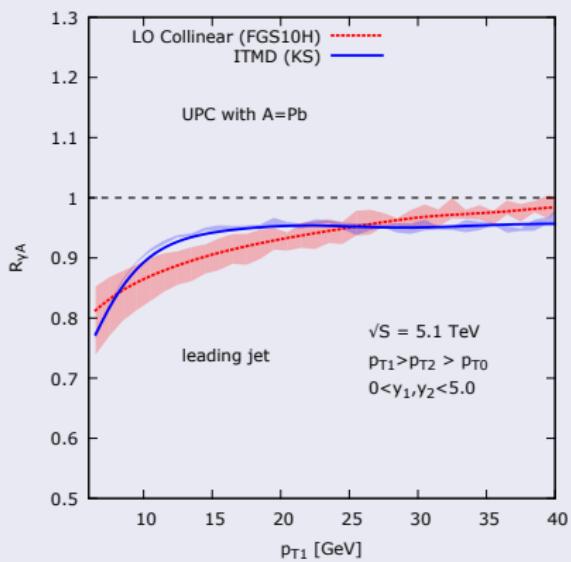
$$R_{\gamma A} = \frac{d\sigma_{AA}^{\text{UPC}}}{Ad\sigma_{Ap}^{\text{UPC}}}$$

where  $A = \text{Pb}$  and the  $d\sigma_{Ap}^{\text{UPC}}$  is with jets going in the nucleus direction.

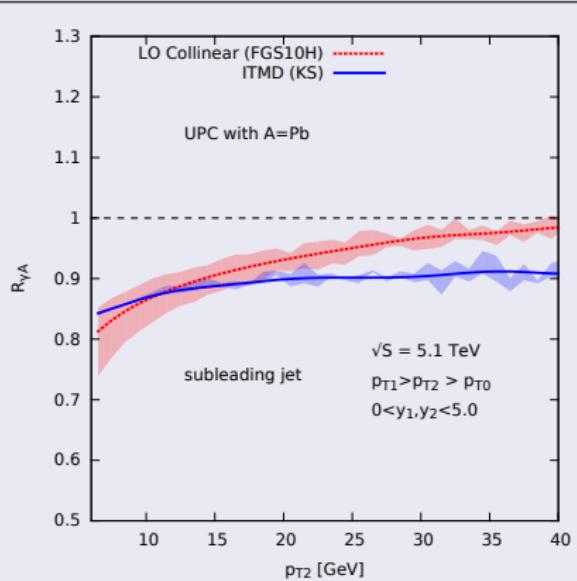
# ITMD for Ultra Peripheral Collisions

Results for nuclear modification ratios  $R_{\gamma A}$

leading jet  $p_T$



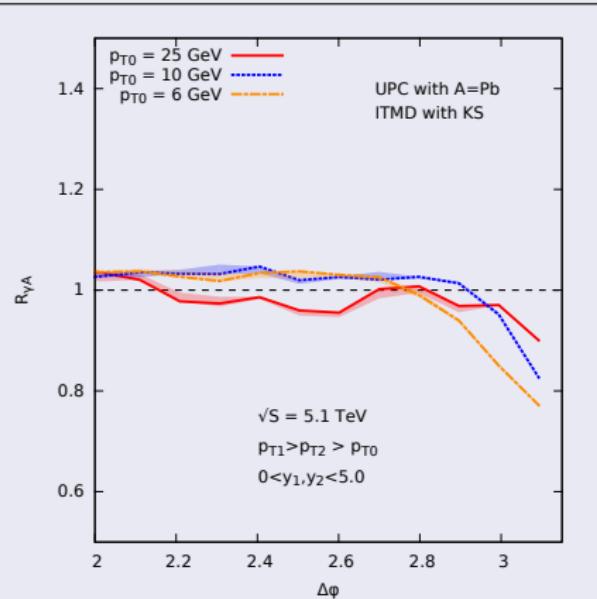
subleading jet  $p_T$



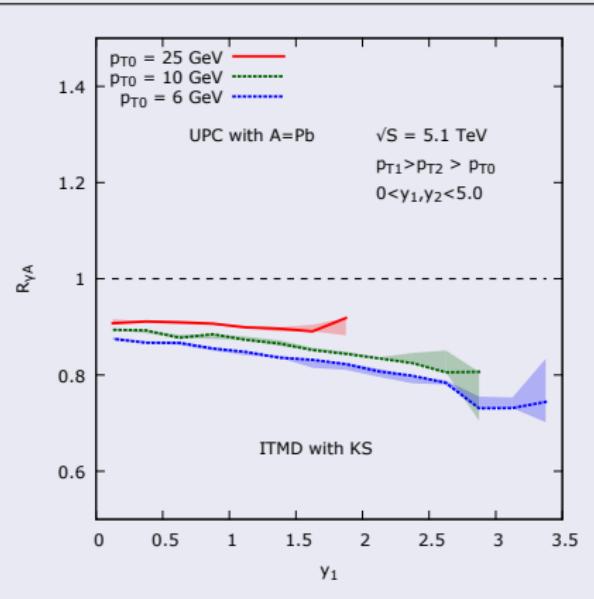
# ITMD for Ultra Peripheral Collisions

Results for nuclear modification ratios  $R_{\gamma A}$

azimuthal disbalance



rapidity



# Summary & Outlook

- Phenomenology in saturation regime for forward dijet production
  - it requires several unintegrated gluon distributions, in particular  $G^{(1)}$  and  $G^{(2)}$
  - at large  $N_c$  in gaussian approximation they are all related
  - so far  $G^{(1)}$  is only accessible through models or through the gaussian approximation from  $G^{(2)}$
  - forward dijets in  $eA$  or UPC probe  $G^{(1)}$  directly
- Monte Carlo implementations of the ITMD framework
  - calculations (within gaussian approximation) give strong saturation effects at LHC in  $pA$  and rather weak but visible in UPC
- Possible further directions:
  - beyond gaussian approximation and large  $N_c$  [C. Marquet, E. Petreska, C. Roiesnel, JHEP 1610 (2016) 065]
  - exact double logs of the Sudakov type [A.H. Mueller, Bo-Wen Xiao, Feng Yuan, Phys.Rev. D88 (2013) 114010]
  - complete evolution of UGD for any  $x$  [I. Balitsky, A. Tarasov, JHEP 1606 (2016) 164]

[A. van Hameren, P. Kotko, K. Kutak, C. Marquet, E. Petreska, S. Sapeta, arXiv:1607.03121]

# BACKUP

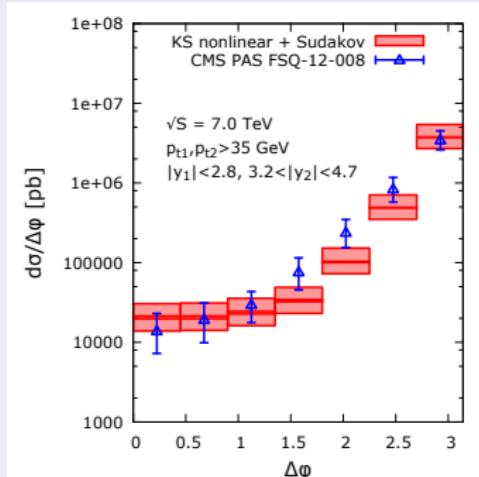
# High Energy Factorization

## Comparison with data

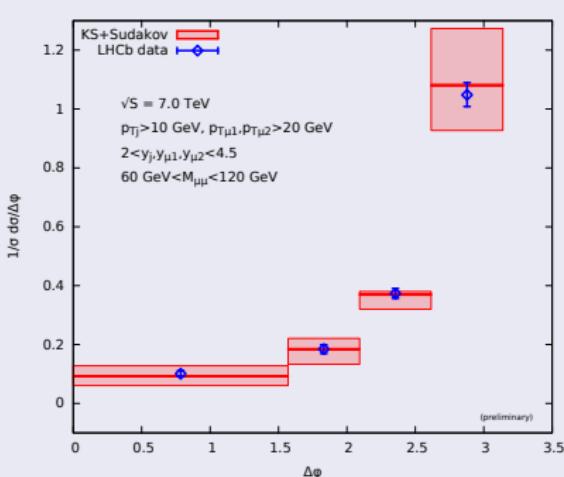
Dijet decorrelations are nicely described by the High Energy Factorization.

[A. van Hameren, PK, K. Kutak, S. Sapeta, Phys.Lett. B737 (2014) 335-340]

forward-central dijets



forward  $Z_0 + \text{jet}$



We can improve TMD factorization by introducing off-shellness to the hard factors.

# Constructing ITMD

## Main steps

- We revise the calculation of TMD gluon distributions using color decomposition of amplitudes

$$\mathcal{M}^{a_1 \dots a_N} (\varepsilon_1^{\lambda_1}, \dots, \varepsilon_N^{\lambda_N}) = \sum_{\sigma \in S_{N-1}} \text{Tr}(t^{a_1} t^{a_{\sigma 2}} \dots t^{a_{\sigma N}}) \mathcal{M}(1^{\lambda_1}, \sigma_2^{\lambda_{\sigma 2}} \dots, \sigma_N^{\lambda_{\sigma N}})$$

$a_i$ - color indices,  $\varepsilon_i^{\lambda_i}$  - polarization vectors with helicity  $\lambda_i$ ,  $S_{N-1}$  - set of noncyclic permutations.

We conclude that there are only two independent TMDs  $\Phi^{(i)}$ ,  $i = 1, 2$  (being a combination of  $\mathcal{F}_{qg}^{(1)}$ 's ) needed for each channel.

- We calculate off-shell gauge invariant color-ordered helicity amplitudes.

Methods for gauge invariant off-shell amplitudes:

[E. Antonov, L. Lipatov, E. Kuraev, I. Cherednikov, Nucl.Phys. B721 (2005) 111-135]

[A. van Hameren, PK, K. Kutak, JHEP 1212 (2012) 029; JHEP 1301 (2013) 078]

[A. van Hameren, JHEP 1407 (2014) 138]

[PK, JHEP 1407 (2014) 128]

[A. van Hameren, M. Serino, arXiv:1504.00315]

# Constructing ITMD

## Color-ordered off-shell helicity amplitudes

In spinor formalism, the non-zero off-shell helicity amplitudes have the form of the MHV amplitudes with certain modification of spinor products:

$$\mathcal{M}_{g^*g \rightarrow gg}(1^*, 2^-, 3^+, 4^+) = 2g^2 \rho_1 \frac{\langle 1^* 2 \rangle^4}{\langle 1^* 2 \rangle \langle 23 \rangle \langle 34 \rangle \langle 41^* \rangle}$$

$$\mathcal{M}_{g^*g \rightarrow gg}(1^*, 2^+, 3^-, 4^+) = 2g^2 \rho_1 \frac{\langle 1^* 3 \rangle^4}{\langle 1^* 2 \rangle \langle 23 \rangle \langle 34 \rangle \langle 41^* \rangle}$$

$$\mathcal{M}_{g^*g \rightarrow gg}(1^*, 2^+, 3^+, 4^-) = 2g^2 \rho_1 \frac{\langle 1^* 4 \rangle^4}{\langle 1^* 2 \rangle \langle 23 \rangle \langle 34 \rangle \langle 41^* \rangle}$$

where  $\langle ij \rangle = \langle k_i - |k_j + \rangle$  with spinors defined as  $|k_i \pm \rangle = \frac{1}{2} (1 \pm \gamma_5) u(k_i)$ .

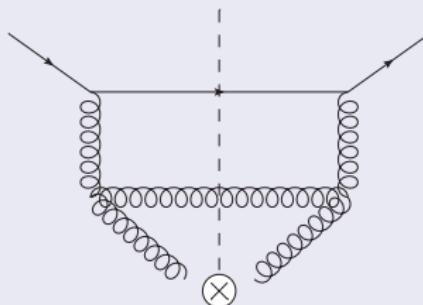
Modified spinor products involve only longitudinal component of the off-shell momentum  $\langle 1^* i \rangle = \langle p_A i \rangle$ . Similar expressions can be derived for quarks.

[A. van Hameren, PK, K. Kutak, JHEP 1212 (2012) 029]

# Generalized TMD Factorization

Example: TMD for a particular diagram

[C.J. Bomhof, P.J. Mulders, F. Pijlman, Eur.Phys.J.C. 47, 147 (2006)]



$$\langle p_A | \text{Tr}\{F^{+i}(\xi) \mathcal{U}^{[+]^\dagger} F^{+i}(0) \left[ \frac{\text{Tr} \mathcal{U}^{[\square]^\dagger}}{N_c} \mathcal{U}^{[+]} + \mathcal{U}^{[-]} \right] \} | p_A \rangle$$